NIH Roadmap

Interdisciplinary Research Centers Workshop

Feb 9th, 2006

Team Structure and Performance

A roadmap for identifying, nurturing and measuring transformative research

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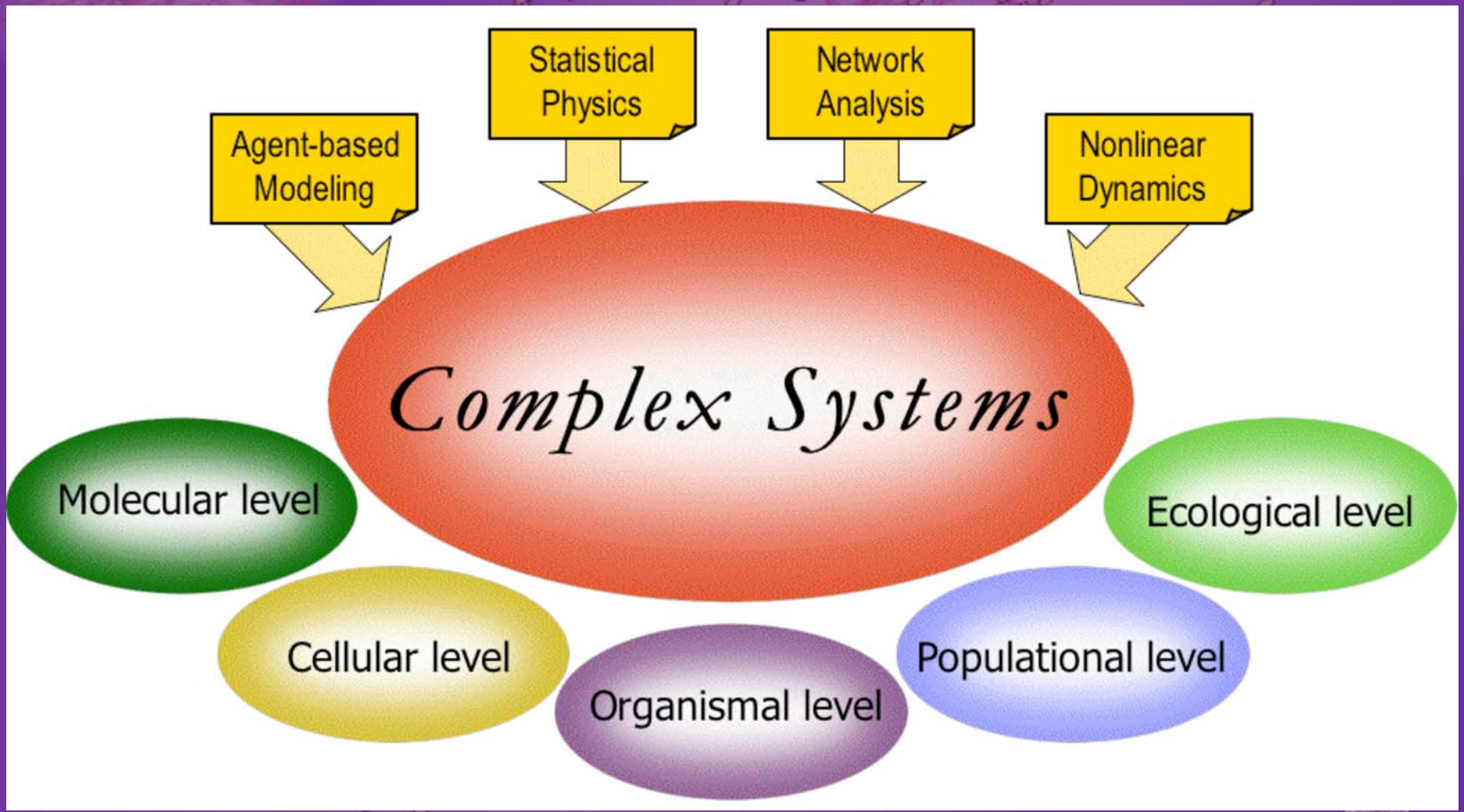
Characterization and modeling of complex systems



Amaral & Ottino, Europ. Phys. J. B **38**, 147 (2004)

Funes, the Memorious (Borges)

"He knew the forms of the clouds in the southern sky on the morning of April 30, 1882, and he could compare them in his memory with the veins in the marble binding of a book he had seen only once…"

"Not only was it difficult for him to see that the generic symbol 'dog' took in all the dissimilar individuals of all shapes and sizes, *it irritated him that the 'dog' of three-fourteen in the afternoon, seen in profile, should be indicated by the same noun as the 'dog' of three-fifteen, seen frontally*."

“Cliff Notes” on the “History of Transformative Discoveries”

- ***Luck***: Right person in the right place at the right time.
- ***Exhaustion of “proper” problems in field***: The end of science syndrome
- ***Interdisciplinary training and collaborations***: “Creativity is spurred when proven innovations in one domain are introduced in a new domain, solving old problems and inspiring fresh thinking.”

Luck as a path for transformative discovery

Christopher Columbus: Columbus' enterprise to find a westward route to Asia grew out of the practical experience of a long and varied maritime career, as well as out of his considerable reading in geographical and theological literature.

He settled for a time in Portugal, where he tried unsuccessfully to enlist support for his project, before moving to Spain. After many difficulties, through a *combination of good luck and persuasiveness*, he gained the support of the Catholic monarchs, Isabel and Fernando.

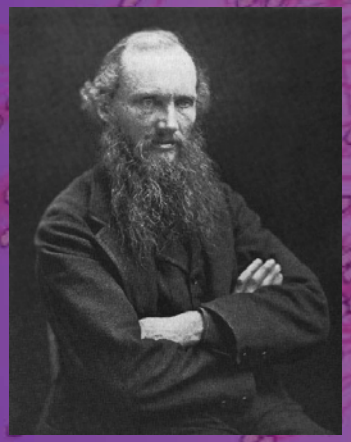
The widely published report of his voyage of 1492 made Columbus famous throughout Europe and secured for him the title of Admiral of the Ocean Sea and further royal patronage. *Columbus, who never abandoned the belief that he had reached Asia*, led three more expeditions to the Caribbean. But intrigue and his own administrative failings brought disappointment and political obscurity to his final years.

Luck as a path for transformative discovery

Alexander Fleming: As far back as the nineteenth century, antagonism between certain bacteria and molds, including Penicillium, had been observed, and a name was given to this phenomenon—antibiosis—but little was made of these observations. A folk tradition using molds in medicine was similarly neglected. In 1928 Alexander Fleming discovered penicillin, but he did not receive the Nobel Prize in physiology or medicine for his discovery until 1945.

Fleming himself did not realize how important his discovery was; for a decade after, he focused instead on penicillin's potential use as a topical antiseptic for wounds and surface infections and as a means of isolating certain bacteria in laboratory cultures. It was left to his fellow Nobelists, Howard Florey and Ernst Chain, to demonstrate in 1940 that penicillin could be used as a therapeutic agent to fight a large number of bacterial diseases wherever they occurred in the human body.

Exhaustion of "proper" problems as a path for transformative discovery



Albert Michelson: In 1894, the experimental physicist Albert Michelson, who later won the Nobel Prize for physics, declared in a speech to dedicate a new laboratory at the University of Chicago: "*The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote... Our future discoveries must be looked for in the sixth place of decimals*."

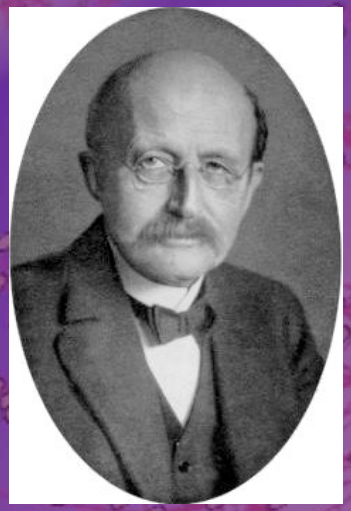
William Thomson (Lord Kelvin): In a lecture to the Royal Institute in 1900, Lord Kelvin declared: "*There is nothing new to be discovered in physics now. All that remains is more and more precise measurement*." He then added that there were "*two small clouds on the horizon*"—the unusual characteristics of a phenomenon known as blackbody radiation and the unexpected results of an experiment conducted by Michelson and Morley in 1887.

Exhaustion of "proper" problems as a path for transformative discovery

Albert Einstein: Einstein had long been convinced that the Principle of Relativity must apply to all phenomena, mechanical or not. His new theory, later called the *special theory of relativity*, was based on a novel analysis of space and time. Einstein theory was able to explain the results of Michelson and Morley's experiments which found no dependence of the velocity of light on body motion.

Max Planck: Planck had been commissioned by electric companies to discover how to maximize light-bulb efficiency. The fundamental question had already been stated by Kirchhoff in 1859: how does the intensity of the electromagnetic radiation emitted by a "blackbody" depend on the frequency of the radiation and the temperature of the body?

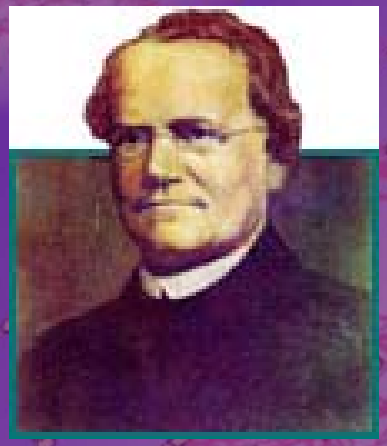
Exhaustion of “proper” problems as a path for transformative discovery



Planck found that he could only derive a satisfactory equation using what he thought was merely a mathematical trick, namely that light is only emitted in "packets". He did not for many years believe that these packets, known as quanta, corresponded with reality.

By December 1900 he was already able to present a theoretical derivation of the law, but this required him to use ideas from statistical mechanics, as introduced by Boltzmann. *So far he had been holding a strong aversion against any statistical interpretation of the Second law of thermodynamics which he regarded as of an axiomatic nature: "... **an act of despair** ... I was ready to sacrifice any of my previous convictions about physics ..."*

Interdisciplinary training and collaborations as a path for transformative discovery



Gregor Mendel: While at the University of Vienna, Mendel had been trained in mathematics and learned how to design experiments and analyze data. The son of a farmer, he had always been interested in plants. So, it is almost natural that in the 1850s, he decided to run an experiment to better understand what kept species distinct and what made it possible for hybrids to form. He bred thousands of pea plants and recorded how traits were passed on from one generation to the next.

Mendel tried to drum up interest in his results but to no avail. *Part of the problem was that botanists of Mendel's time were not accustomed to statistics being applied to natural history, and so they would't or couldn't recognize the importance of Mendel's discovery*.

The patterns that Mendel saw were there in nature for anyone to see. Darwin himself noted a three-to-one ratio in the colors of snapdragons. But for all his genius, Darwin didn't realize the importance of that ratio.

Interdisciplinary training and collaborations as a path for transformative discovery

John von Neumann: A Hungarian–German mathematician and polymath who made important contributions in *quantum physics, functional analysis, set theory, computer science, economics and many other mathematical fields*.

He was a pioneer of the modern digital computer and the application of operator theory to quantum mechanics (see Von Neumann algebra), member of the Manhattan Project Team, creator of game theory and the concept of cellular automata.

Interdisciplinary training and collaborations as a path for transformative discovery

John von Neumann: Although John von Neumann was without doubt "the father of game theory," the birth took place after a number of miscarriages. This paper, elegant though it is, might have remained a footnote to the history of mathematics were it not for collaboration of von Neumann with Oskar Morgenstern in the early '40s. Their joint efforts led to the publication by the Princeton University Press of the 616-page Theory of Games and Economic Behavior.

Robert J. Leonard, who wrote an account of the interactions between the two, surmised that "***had von Neumann and Morgenstern never met, it seems unlikely that game theory would have been developed***." If von Neumann played both father and mother to the theory in an extraordinary act of parthenogenesis, then Morgenstern was the midwife.

Implications for policy

- ***Luck***: Questionable if there is a role for policy in this...

- ***Exhaustion of "proper" problems in field***: If the researchers in a field are talking about end of science scenarios, if the advances are on the six decimal place, it would appear that the right policy is to get resources out of the field…

- ***Interdisciplinary training and collaborations***: In my view, this option holds the most potential for policy intervention and the highest chances of success. If done right!

Challenges to interdisciplinary collaboration, i.e., attitudes that need to be fought

- ***She is not deep/focused***
- ***There are so many co-authors, did he really contribute anything?***
- ***It is better to do it (amateurishly) alone than (competently) with others***
- ***If you have not read those/my papers you cannot possibly have anything worthwhile to contribute***
- ***How can you possibly not know what 'a kinase,' 'a soliton,' 'a Poincare plot,' 'simulated annealing' is?***
- ***It is my way or the highway***

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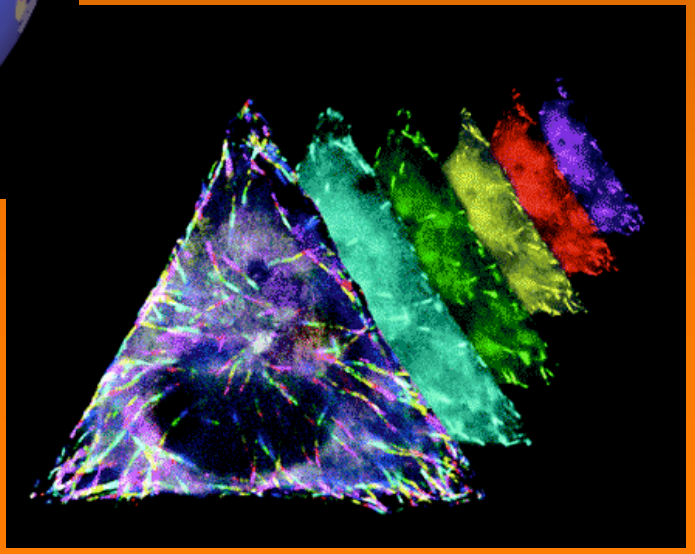
To bring collaborative scientists together to tackle major scientific questions from an interdisciplinary perspective

Social Systems
& Organizations

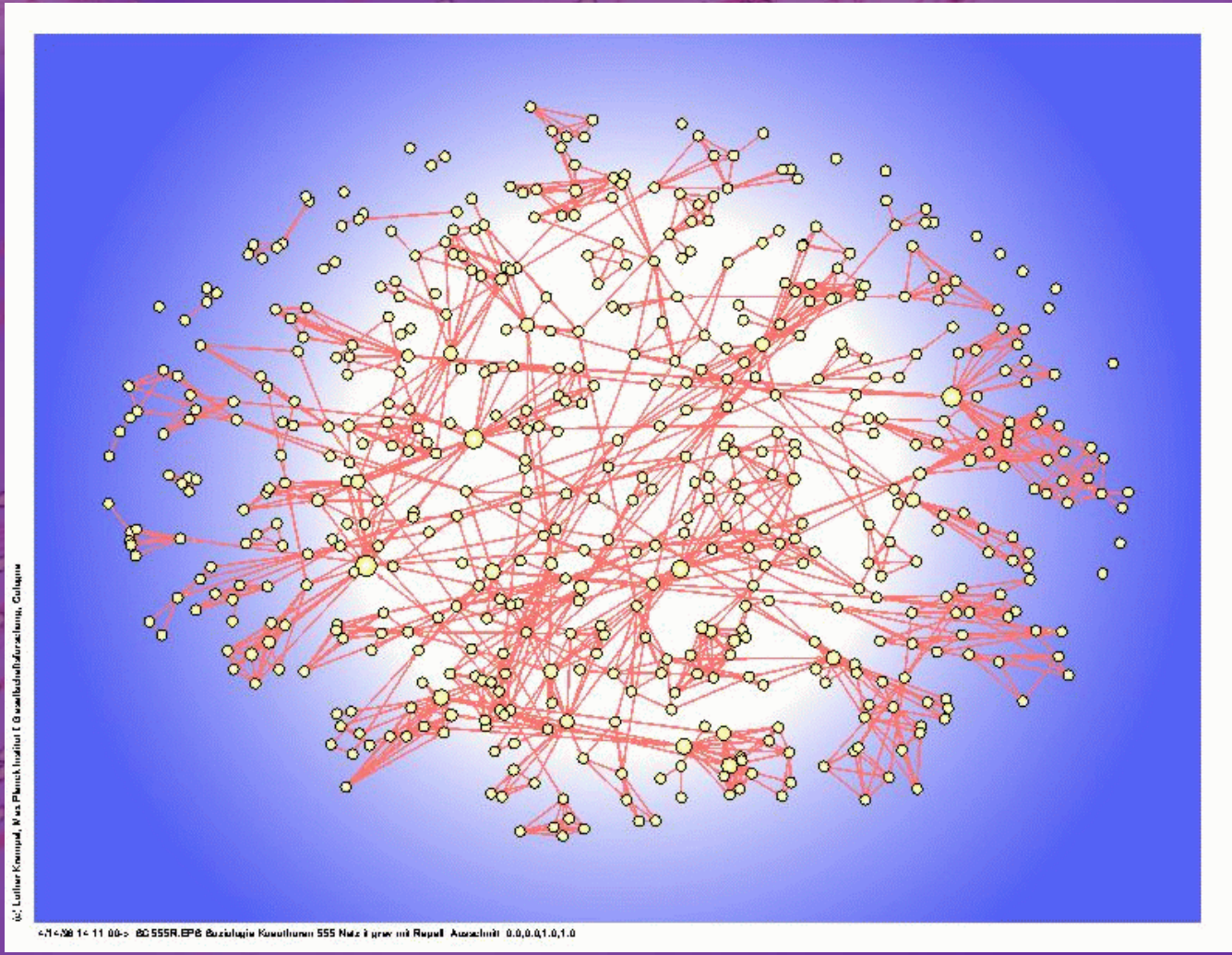
Biology &
Medicine

Physical &
Chemical Systems



Embarrassing avoidable deadly failure

Collaboration networks



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Courtesy of L. Krempel (MPI, Germany)

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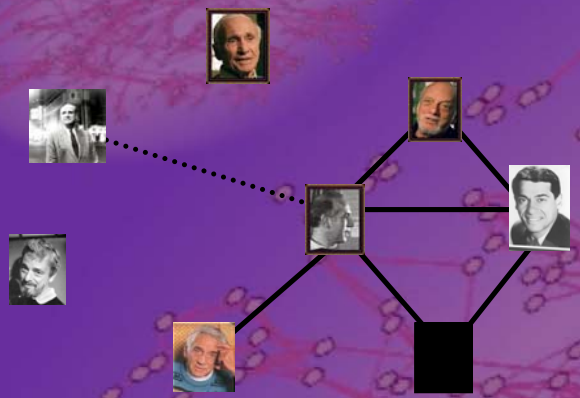
How does one assemble effective teams?

- How many people?
- What backgrounds and what skills?
- How similar/dissimilar in personality/style?
- What levels of experience?

Team size can vary quite broadly



Team size is 8

Team size is 2 (well, 4)

SLOAN DIGITAL SKY SURVEY: EARLY DATA RELEASE

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Team size is 192

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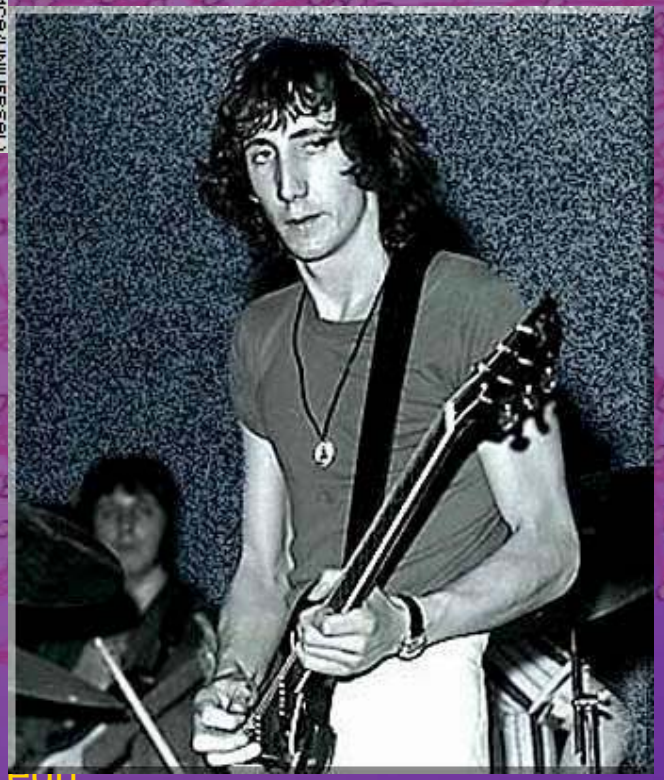
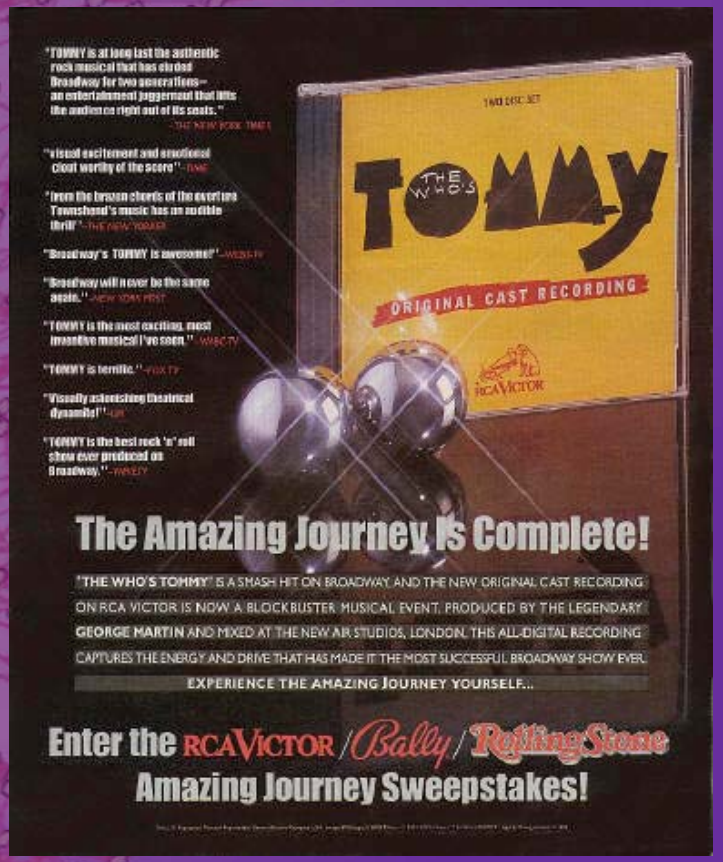
Measuring diversity is “tricky”

Expertise is in the eye of the beholder





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Quantifying expertise and diversity

- ***p*** probability of a team member being an incumbent/expert
  - High *p*, high expertise
  - Low *p*, low expertise

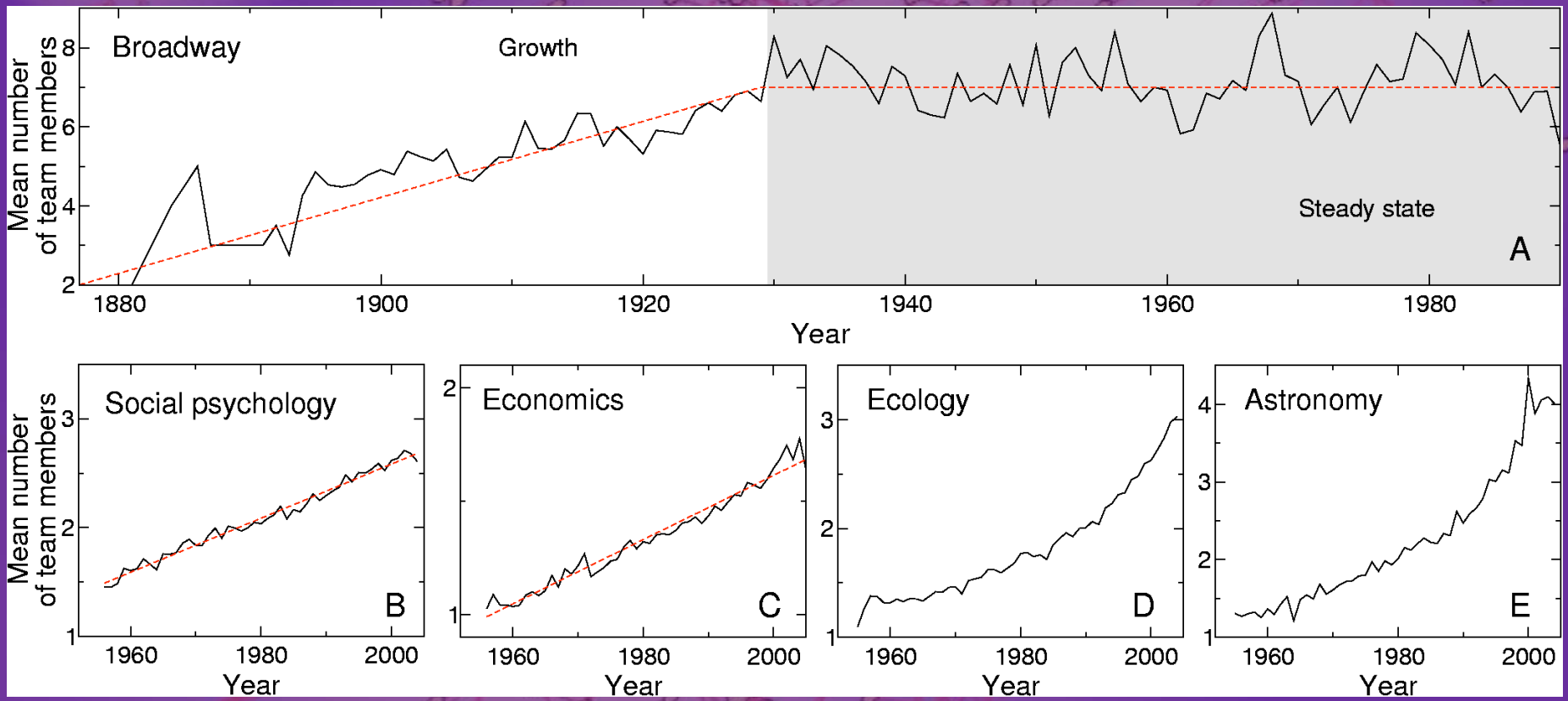
- ***q*** propensity to repeat past collaborations rather than initiate new ones
  - High *q*, low diversity
  - Low *q*, high diversity

Guimera, Uzzi, Spiro & Amaral, Science **308**, 697 (2005)

Empirical data

Field	Period	#Teams	Agents	Journals
Broadway	1877-1990	2258	4113	----
Social psychology	1955-2004	16526	23029	7
Economics	1955-2004	14870	23236	9
Ecology	1955-2004	26888	38609	10
Astronomy	1955-2004	30552	30192	6

Team size increases over time



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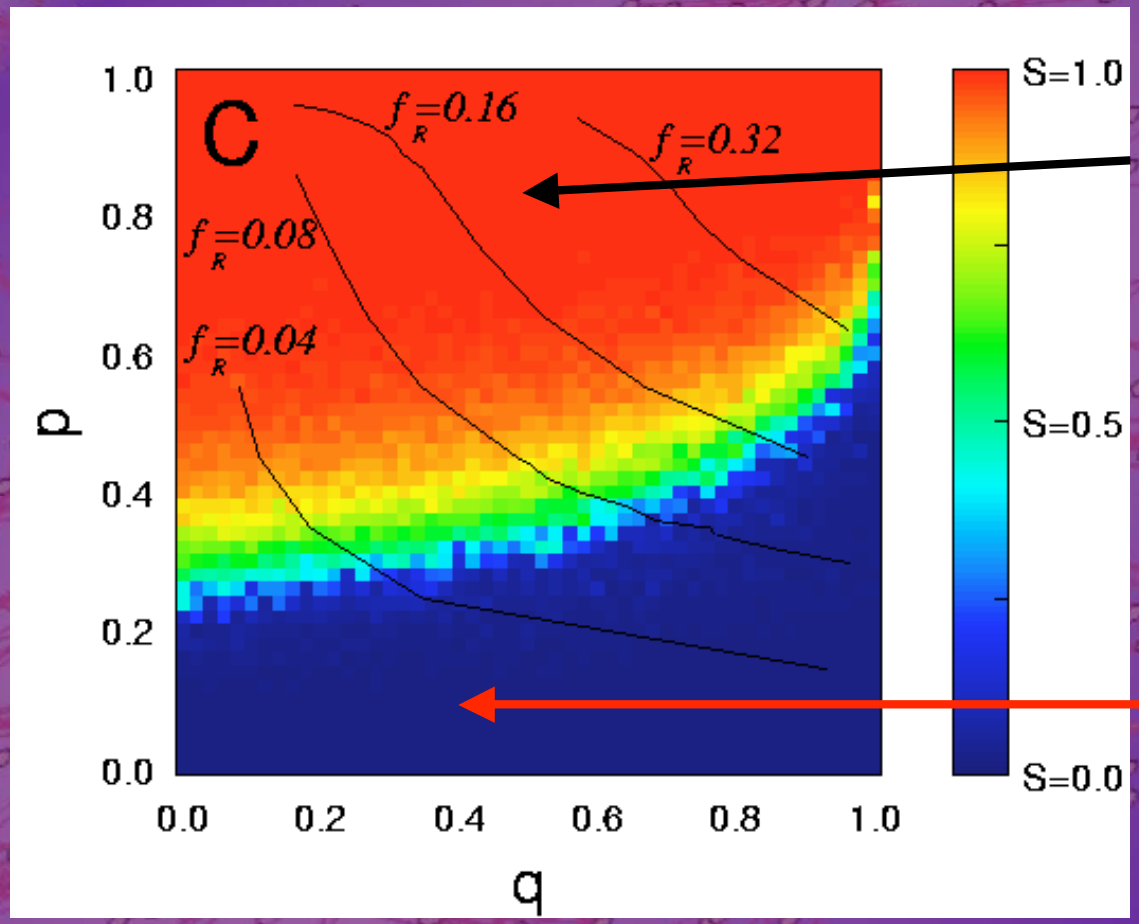
The “invisible college”



Expertise

Diversity

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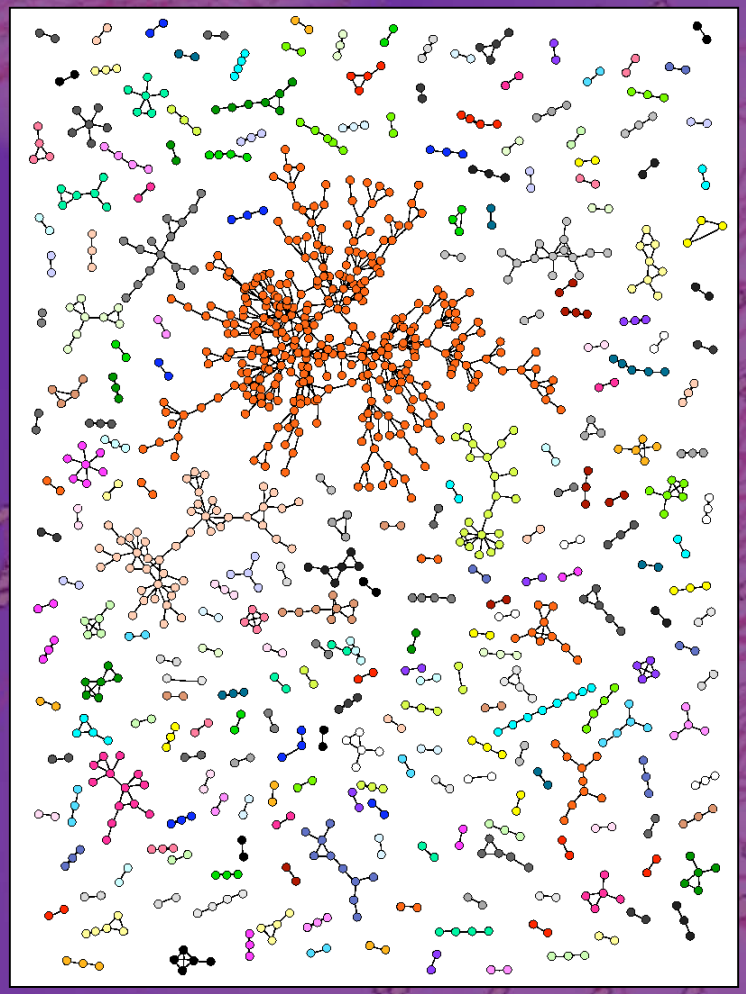
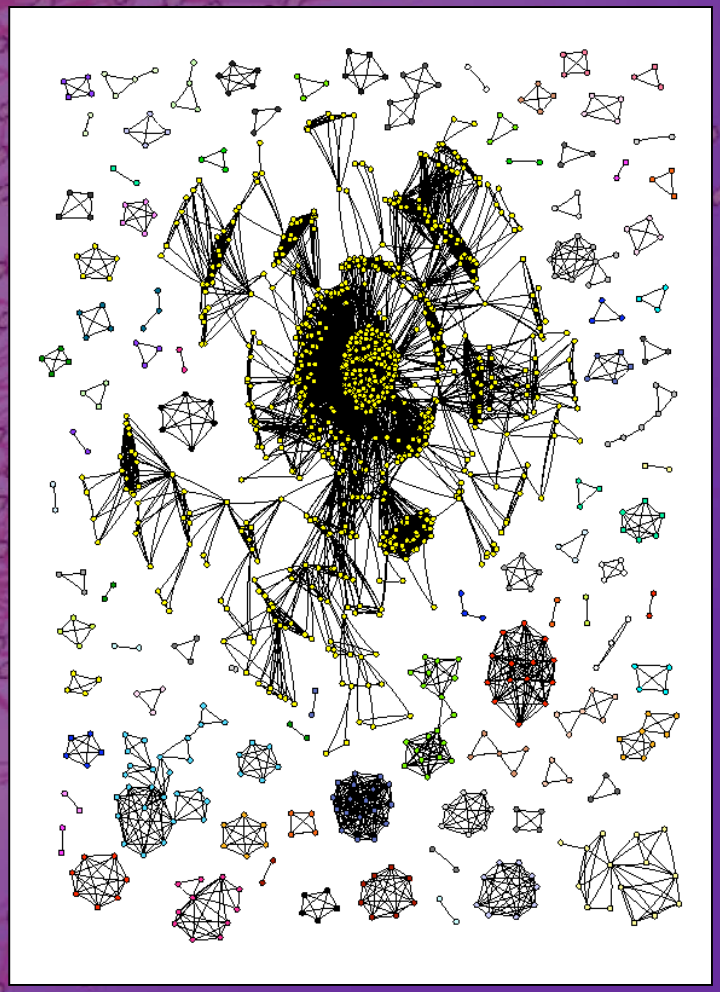
Different assembly mechanisms yield different collaboration networks



Collaboration network of *Econometrica* authors



Collaboration network of *Astronomical Journal* authors

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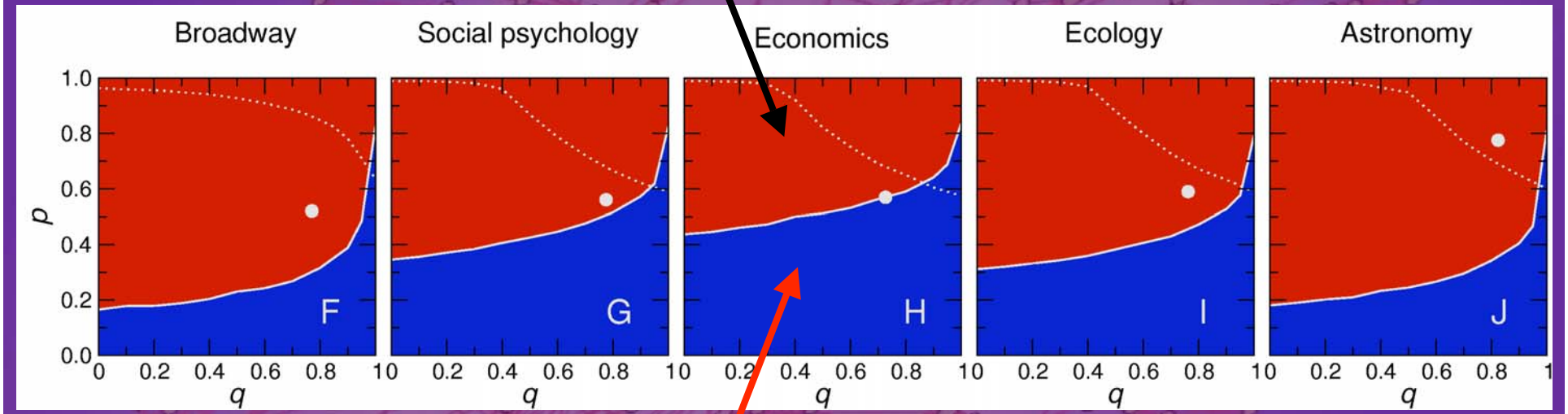
Most fields live close to the edge



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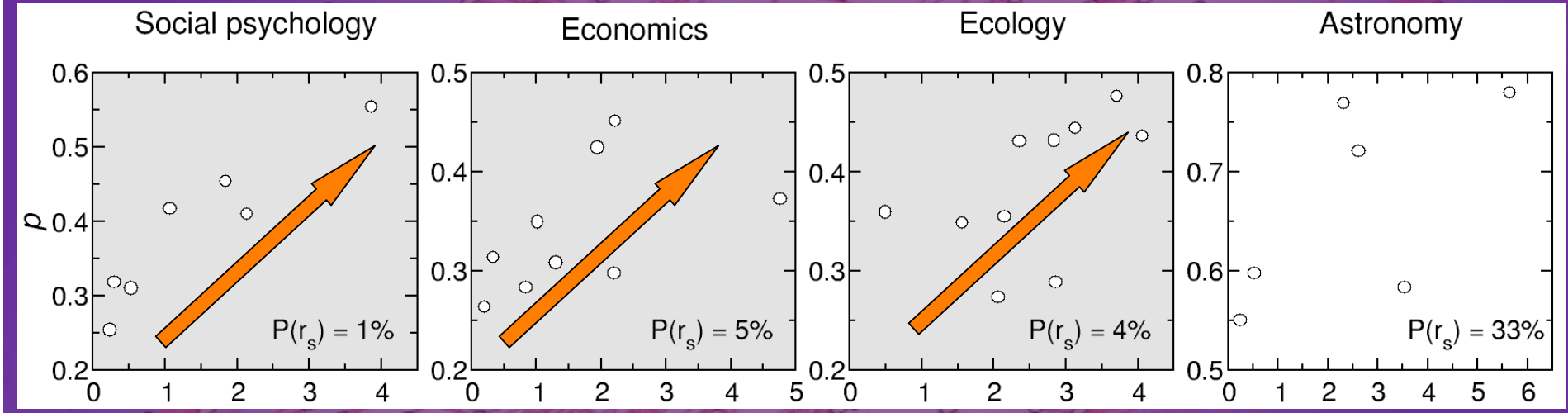
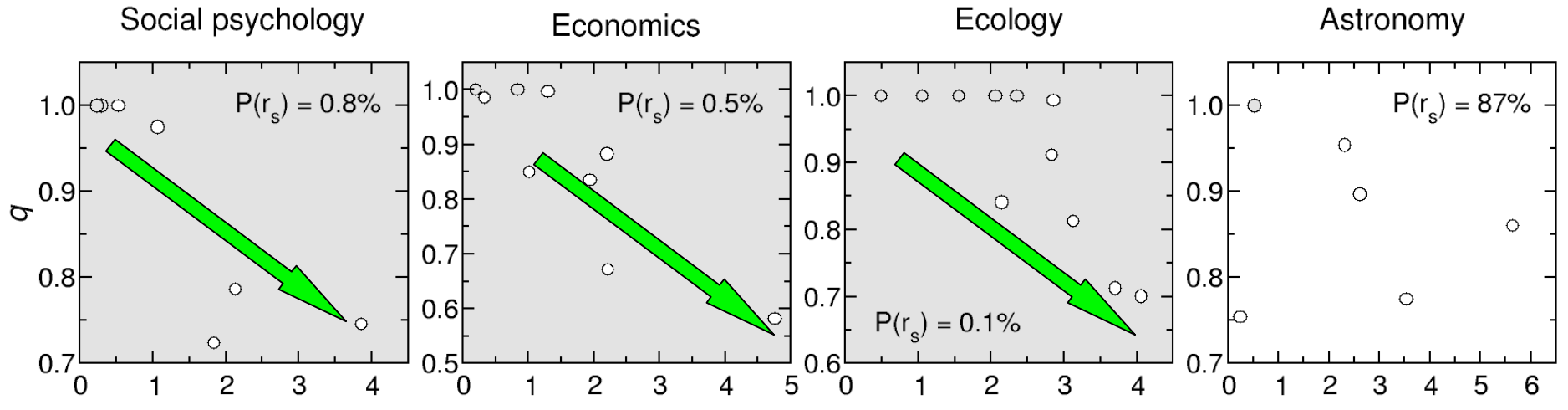
Fraction of incumbents predicts quality of output



Impact factor - a (bad) proxy for journal quality

Guimera, Uzzi, Spiro & Amaral, Science **308**, 697 (2005)

Propensity to establish new collaborations with other incumbents predicts quality of output



Impact factor - a (bad) proxy for journal quality

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Take home message

- Performance is ***positively correlated*** with expertise and diversity in different fields
- Different creative fields seem to approach similar average levels of expertise and diversity
- "Invisible colleges," which emerge for systems with diverse teams, enable percolation of knowledge

What needs to be developed...

- Methods to measure success of interdisciplinary collaborations
- Methods to compare research quality across fields (popularity, reputation, etc..)
- Methods to identify transformative research early

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- J. S. McDonnell Foundation Collaborative Award